High-Precision and High-Efficiency Measurement Method of Accelerator Tunnel Control Network Based on Total Station

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Introduction

Introduction to large-scale accelerator devices

Table 1 Comparison of CSNS, HEPS, and CPEC Accelerator Facilities

	CSNS	HEPS	LHC	CEPC
Purpose	Neutron scattering	High-energy photon	protons or heavy ions collision	Electron-positron collision
Energy Level	1.6 GeV proton beam	Planned 6 GeV electron beam	13 TeV proton beam	Planned 240 GeV center-of-mass energy
Ring circumference	228 meters	1360.4 meters	27 km	~100 km
Accuracy requirement	150 μm	50 μm	150 μm	100 μm
Control network survey time (2 groups)	5 days	36 days	563 days	~2000 days
Construction	Completed and operational	Under construction	Completed and operational	Proposed, planning and design phase


(a)


(b)

As the scale of alignment increases, it is crucial to improve efficiency while maintaining accuracy.

Introduction of total station

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Table 2 Parameters of the Total station TM50i

Angle Measurement		
Accuracy (Hz/V)	Absolute encoding, continuous, quadruple-axis compensation	0.5" (0.15mgon) or 1" (0.3mgon)
Distance Measurement		
Range	Prism（GPR1, GPH1P）	1.5 m to3500 m
	Non-prism/Any surface	1.5m to ＞1000m
Accuracy/Measurement time	Single prism	0.6mm＋1ppm / typical 2.4 seconds
	Any surface	2mm＋2ppm / typical3 seconds
Beam size	50 m	8mm×20mm
Measurement technology	Phase-based system analysis technology	coaxial, red visible light
Imaging		
Wide-angle camera and telescope camera	Sensor	5-megapixel CMOS sensor
	Field of view (Wide-angle camera/Telescope camera)	19.4° / 1.5°
	Frame rate	Up to 20 frames per second
Motor		
Direct drive, piezoelectric ceramic technology	Rotation speed/ Face change time	Maximum180° （200 gon）per second / typical 2.9 seconds
Long-range automatic target recognition (ATR)		
ATR mode Range	Prism（GPR1, GPH1P）	3000 m
	360° prism（GRZ4, GRZ122）	1500 m
Accuracy/measurement time	ATR angle measurement（Hz/ V）	0.5“ or 1"/ typical 3-4 seconds

Only Angle observation + distance constraint

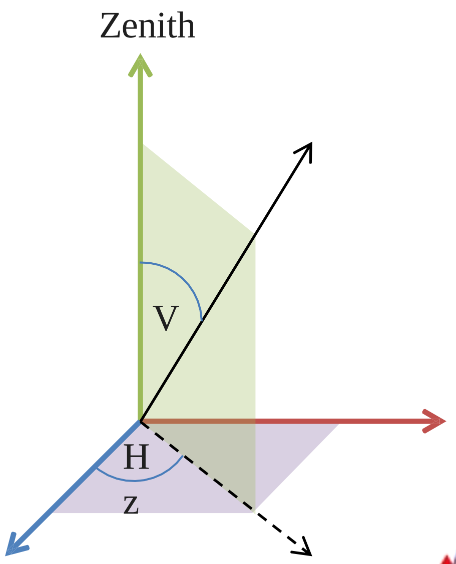
PART 02

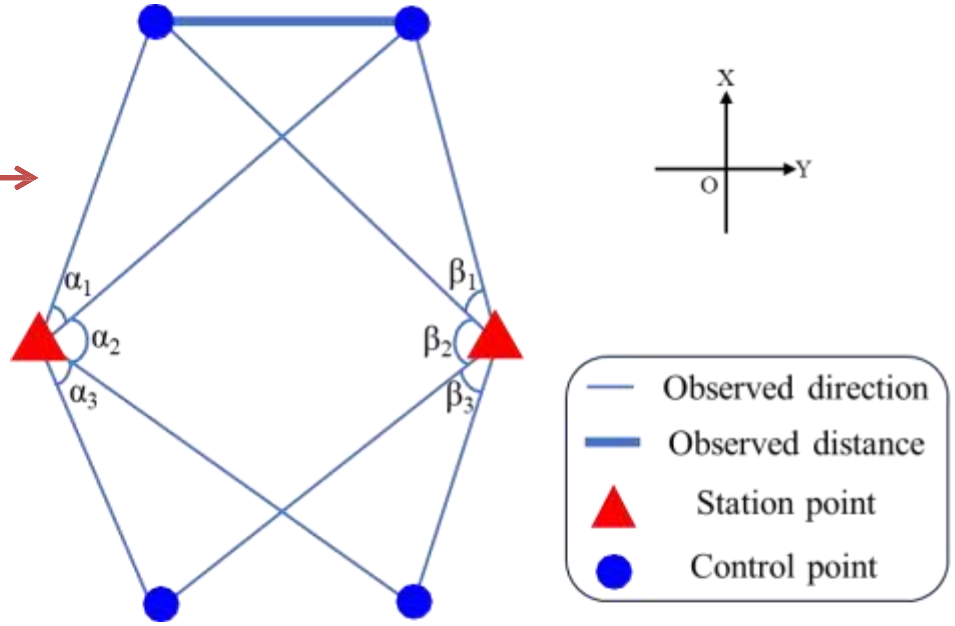
Angle Intersection Method

Principle of Angle Intersection

Measurement/ Observation:

- Distance constraint (Fixed scale)
- Directions
- Angles (as differences of directions)
  - Horizontal
  - Vertical or Zenith





Calculations / Estimations:

- Distances
- Angles

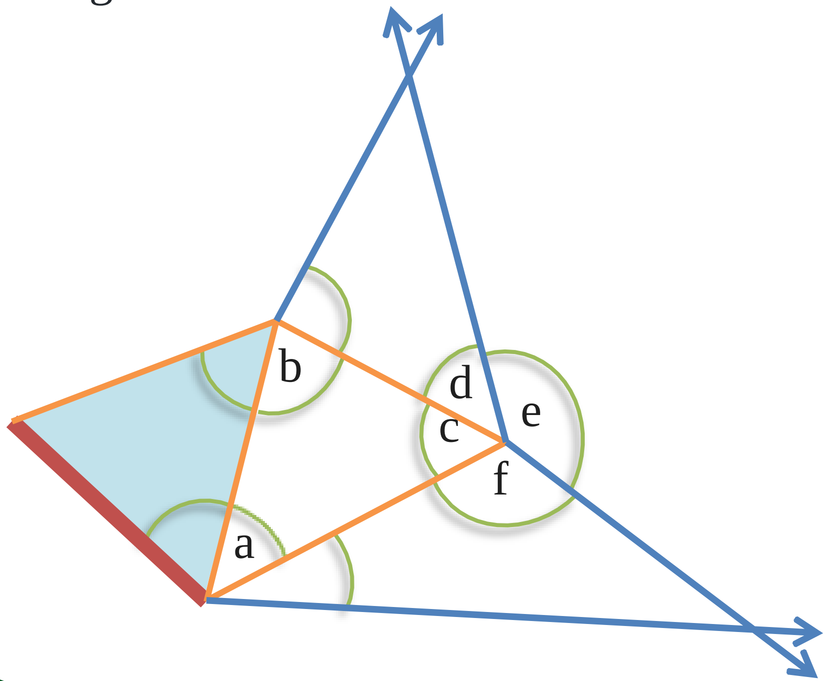
\+ Coordinates w.r.t a reference system

Angle Intersection Method

Mismatch between theoretical and measured values in triangulation:

Closing error

- $a + b + c \neq 180^\circ$
- $c + d + e + f \neq 360^\circ$



<u>Variation between repetitive Observations:</u>

- Environment → Constant temperature
- Instrumentation → Higher accuracy
- Observer → Avoid changes due to observers

Automatic target recognition

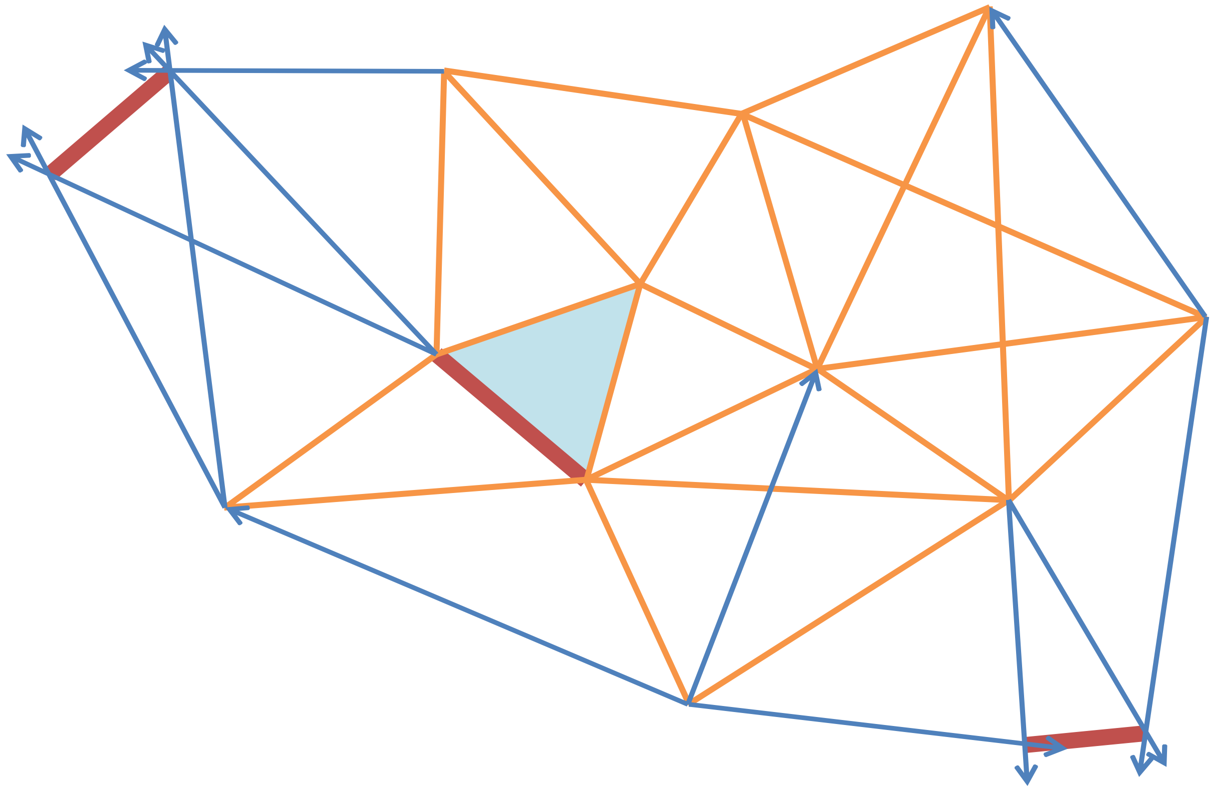
Challenges

✕ Multiple factors accumulation cannot guarantee repeatable accuracy.
✕ The angle observation process requires the observer to have proficient measurement skills.

Problems of Angle Intersection

Problems:

Error propagation +accumulation



Solutions:

- **Observations enough**
- **Observations repetition**
- **Observations redundance**
- **Baseline in propre location**
- **Automatic target recognition (ATR)**
- **Adjustment method**

In view of the above principles and methods, the high precision measurement method of accelerator tunnel control network based on Angle observation of total station is studied.

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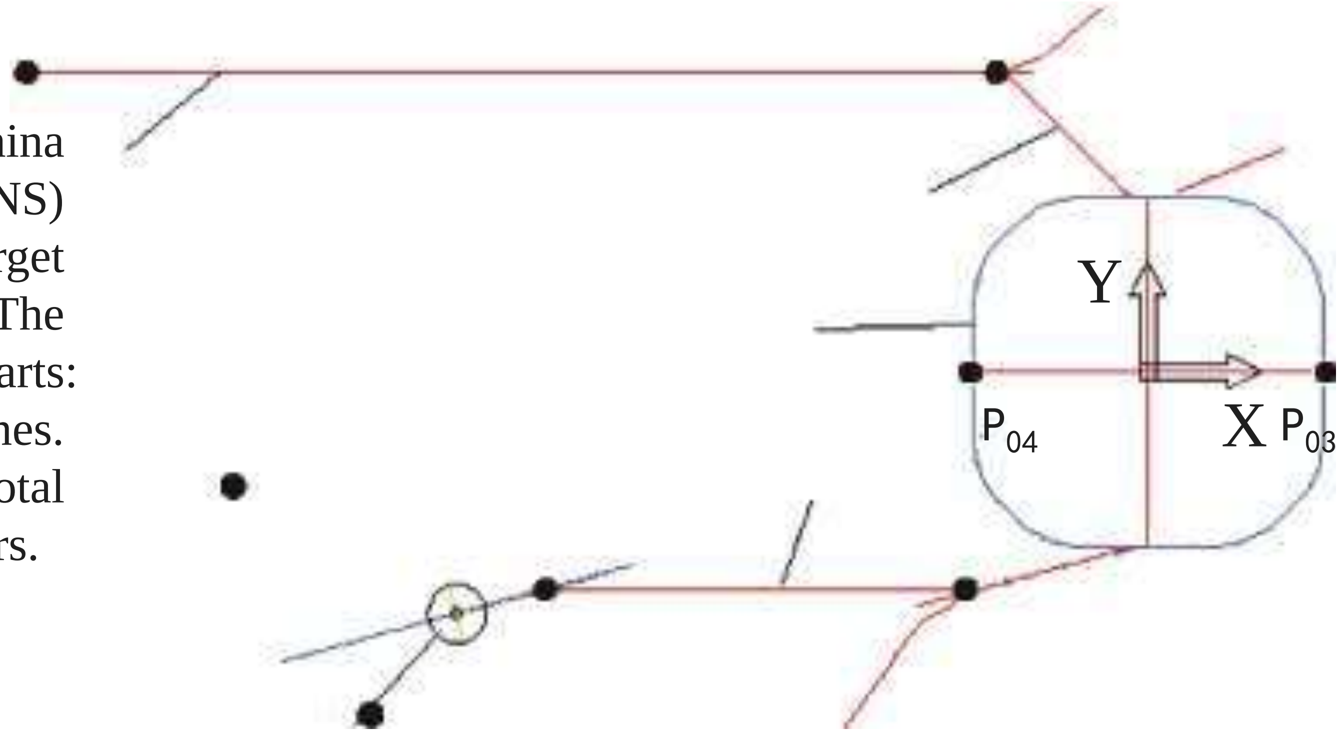
Results and discussions

China Spallation Neutron Source

CSNS device coordinate system

The overall system of the China Spallation Neutron Source (CSNS) consists of an accelerator, target station, and spectrometer hall. The accelerator is divided into three parts: Linac, RCS ring, and transport lines. The CSNS beamline has a total length of approximately 650 meters.



CSNS Ring Tunnel Control Network

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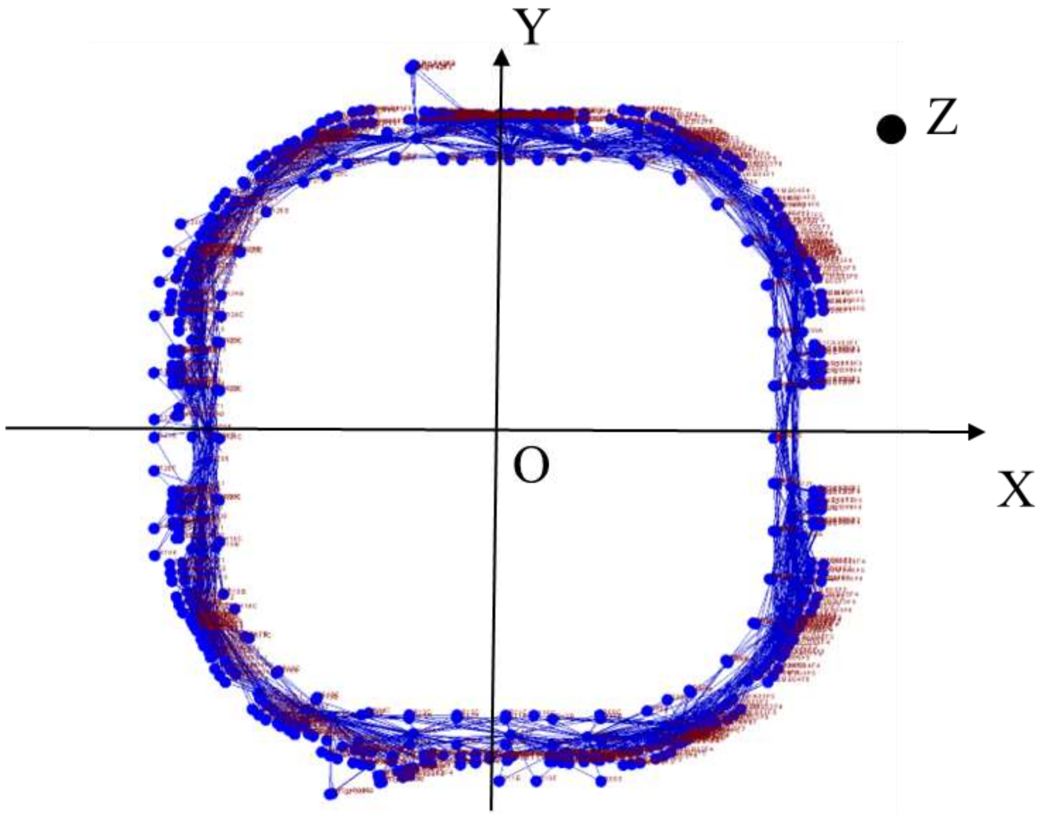
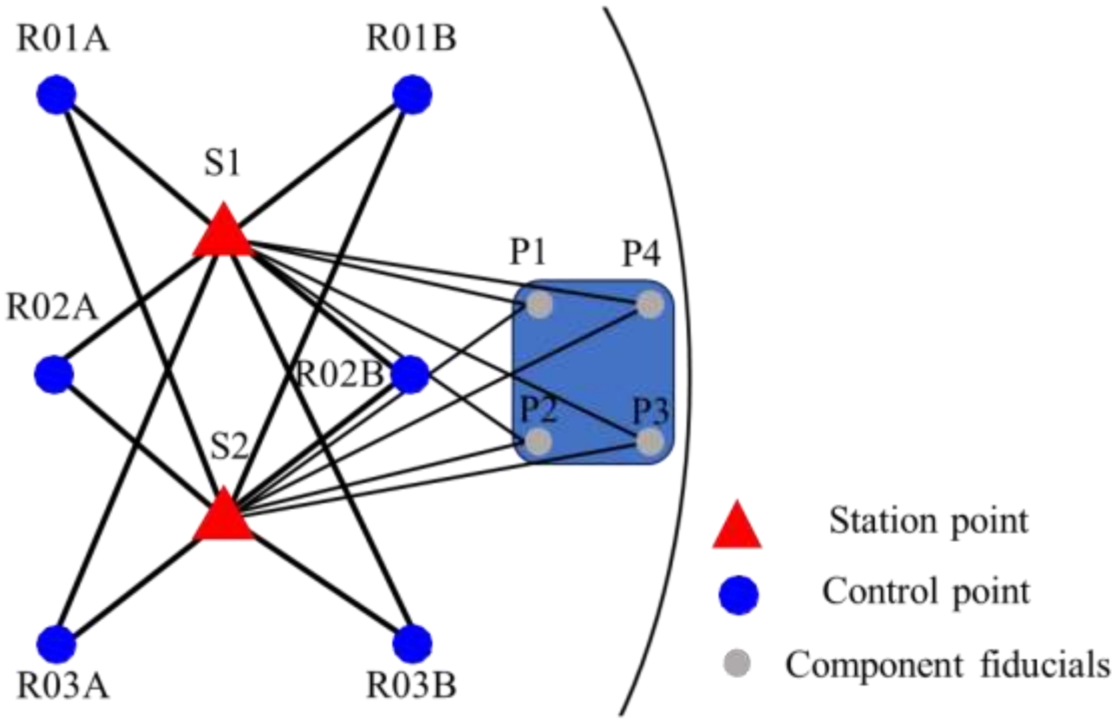


We used the control points to determine the instrument attitude. The transfer station is bonded, and then the equipment points in the control network are measured.

Since the total station has the same angle measurement range as the laser tracker, we replace the laser tracker with the total station. The adjustment results from the laser tracker are used as the theoretical coordinate values, and the station positions of the laser tracker are used as the station positions for the total station. For each station, all the corresponding horizontal angle and zenith observations are generated for the points measured by the laser tracker, with an additional random observation error of 1″. These simulated observations are taken as the total station observations for all points within the tunnel.

Station Setting System of Total Station in Tunnel



Station Setting System of Total Station in Tunnel

TM50 I and ceramic balls

Leica μbase laser rangefinder (10 μm)

Results of simulation survey with total station

- Selected and used comprehensive measurement data of CSNS RCS ring tunnel by laser tracker AT403.

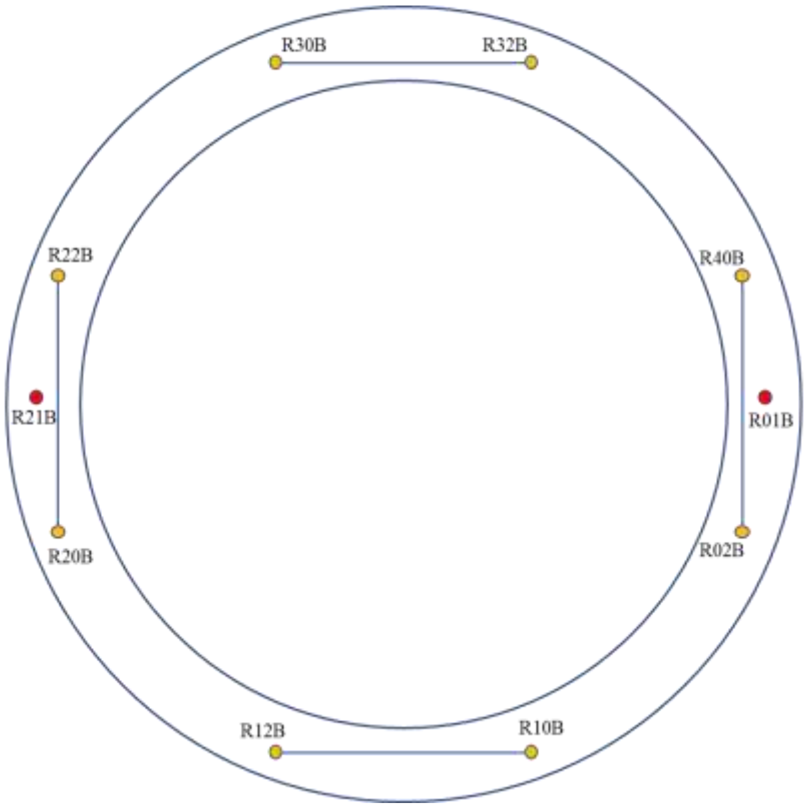
Table 3 Adjustment results of Laser tracker

	Point accuracy /mm			
	Semi-Major Axis	Semi-Minor Axis	Elevation	Planar Error
RMS	0.045	0.025	0.028	0.051
Average	0.045	0.024	0.027	0.050

It can be seen from the results that the point position error in the plane is 0.051 mm, the point position error in the elevation is 0.028 mm.

Then, the simulated observations of the total station were obtained to obtain the corresponding angle observations. By adding distance baselines, the overall accuracy of the total station Angle observation tunnel control network was explored.

Multiple standard distances constraints



The previous observations were all angular observations without distances, so it is necessary to add distances constraints to restrict the overall size of the control network.

Using the μBase rangefinder, we measured the distances. We obtained 4 sets of distance observations, which serve as distance constraints. Next, in the 3D calculation by software Starnet, we fixed the three coordinates of the permanent point P_{04}(R21B) and the Y-coordinate of the permanent point P_{03}(R01B) as known data to determine the position and orientation of the device coordinate system. The approximate size of each constraint is 10 meters.

Table 4 Angle observation adjustment results using four length scale constraints

	Coordinate deviation/mm			Point error/mm		
	dx	dy	dz	Semi-Major Axis	Semi-Minor Axis	Elevation
RMS	0.132	0.108	0.011	0.390	0.174	0.039
Average	0.051	-0.078	0.000	0.370	0.164	0.038

Total station tunnel control network measurement

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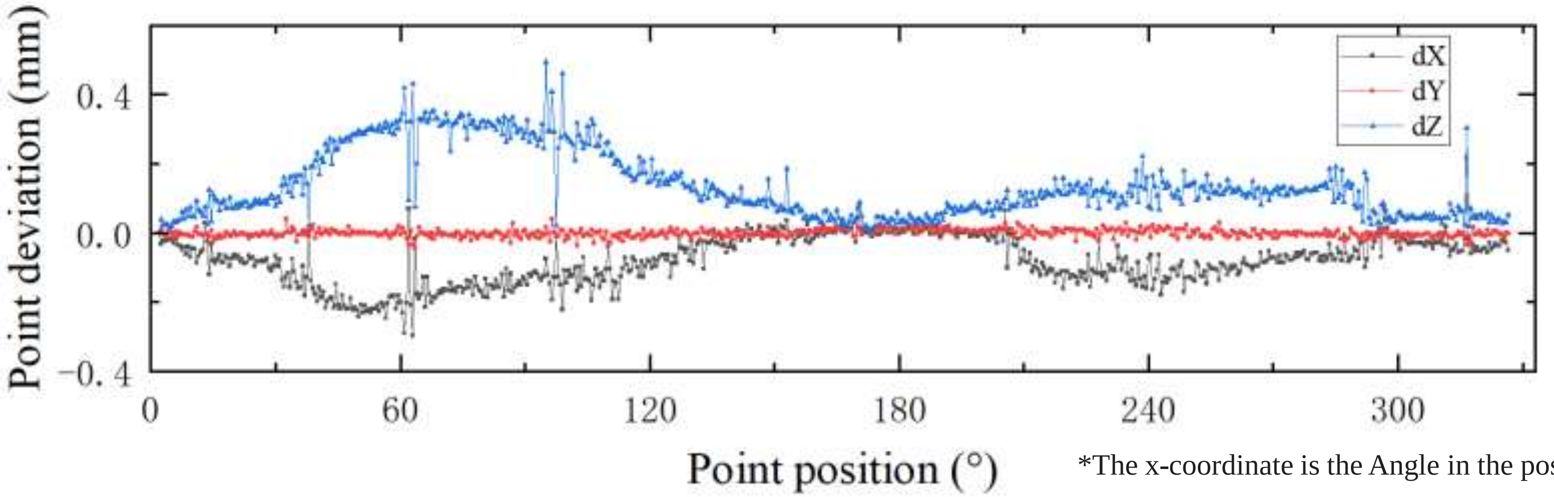

*The x-coordinate is the Angle in the positive direction of the X-axis

Using only four length constraints for the entire control network leads to significant point deviations. The point deviations are smaller near the length constraints around permanent points R01B and R21B. Additional constraints are needed for the circular tunnel control network.

We introduce a closed-loop planar multi-length network for the entire circular tunnel. The starting point is chosen as permanent point P03 (R01B), and every other ground control point is connected. The first length baseline is R01B-R03A, followed by R03A-R05A, ..., R19A-R21B, R21B-R23A, ..., R39A-R01B, and finally returning to the permanent point R01B.

Table 5 Angle observation adjustment results using multiple length scale constraints

	Coordinate deviation/mm			Point error/mm		
	dx	dy	dz	Semi-Major Axis	Semi-Minor Axis	Elevation
RMS	0.071	0.052	0.015	0.150	0.050	0.037
Average	-0.020	0.007	-0.009	0.104	0.048	0.037

Plane Straight-line Triangulation Network

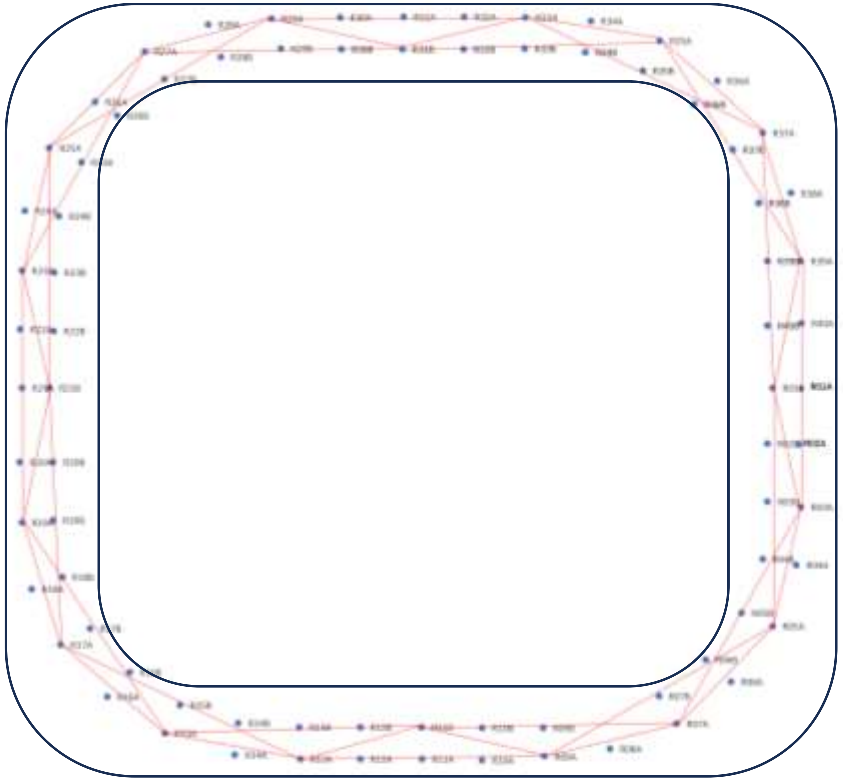

Table 6 Adjustment Results constrained by plane straight-line triangulation network

	Point error/mm		
	Semi-Major Axis	Semi-Minor Axis	Elevation
RMS	0.137	0.030	0.037
Average	0.078	0.028	0.036

The planar point accuracy has been further improved to 0.140 mm, but there are still some points with larger point errors and deviations in coordinates. Out of the total of over 700 control points, we sequentially examined 38 points with point errors greater than 0.15 mm.

By observing their angle intersection forms, we found that all these points with large planar point errors had only two angle observations for intersection. The size of the intersection angles was less than 20° . It was observed that the direction of the larger point errors was generally consistent with the observation direction. We deleted the observations without suitable intersections.

Table 7 Adjustment Results constrained by plane straight-line triangulation network after optimization

	Coordinate deviation/mm			Point error/mm		
	dx	dy	dz	Semi-Major Axis	Semi-Minor Axis	Elevation
RMS	0.022	0.022	0.012	0.060	0.029	0.035
Average	0.000	0.003	-0.003	0.055	0.028	0.035

Plane Straight-line Triangulation Network

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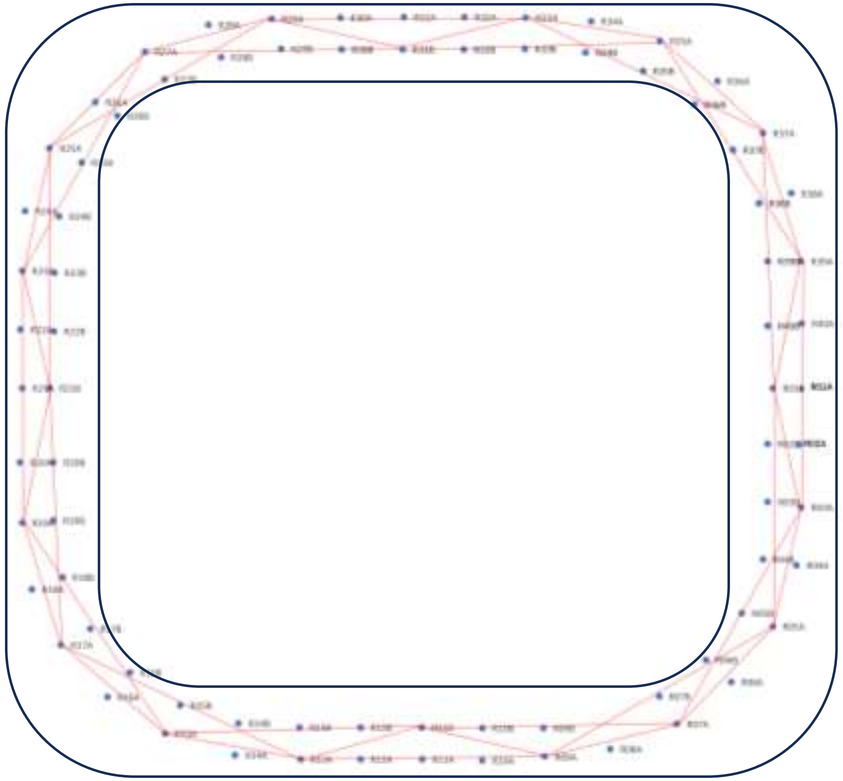


The measurement capability of the control network in the tunnel is almost equivalent to that of the laser tracker. The maximum planar point error has been reduced from 1.607 mm to 0.146 mm, improving the reliability and overall accuracy of the control network. The improvement from 0.162 mm to 0.066 mm suggests that the adoption of updated measurement methods has led to a considerable advancement in the planar point accuracy.

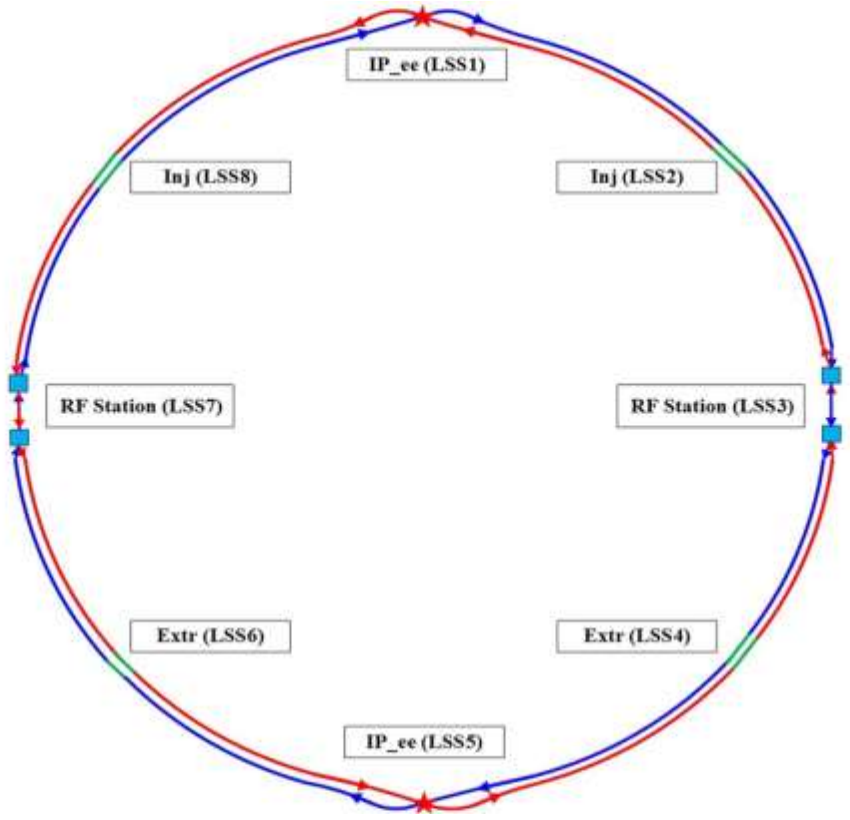
Table 8 Comparison of three methods for planar point accuracy

	Planar Point Accuracy /mm		
	Four length scale constraints	Plane multilength network	Plane straight-line triangulation network
RMS.	0.427	0.162	0.066
Average	0.404	0.115	0.062
Max.	1.607	1.533	0.146
Min.	0.000	0.000	0.000

The absolute values of maximum and minimum coordinate deviations are almost less than 0.1 mm when the maximum point error is less than 0.146 mm. This indicates that under a certain point error, the probability of experiencing significant coordinate deviation is relatively low.

Discussions on the alignment efficiency

High-Precision and High-Efficiency Measurement Method of Accelerator Tunnel Control Network Based on Total Station Angle Observation



If there are 10 groups of the total station with 2 individuals for each group, each group will set up measuring stations every 6 meters. They start measurements each night, spending one hour per station. It would be possible to measure 10 stations per night. In this scenario, the entire 100 kilometers control network measurements task could be completed in approximately 167 days. If using the laser tracker, it would be possible to measure 4 stations per day in order to not occupy much work time. 420 days is required in order to complete this task.

Table 9 The project duration with different methods

Method	Number of people	Duration /Days
Total station angle measurement	20	167
Laser tracker manual measurement	20	420

As shown in Table 9, by utilizing the total station angle measurement method, we can significantly reduce control network measurements duration.

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Conclusions and outlooks

Conclusions

1. Using Plane Straight-line Triangulation Network, the method attains a planar point error of 0.066 mm after optimization. This is comparable to that obtained by a laser tracker for the control network of the CSNS ring tunnel.
2. Analyzing the elevation point errors, we can see that when different constraints are added, the elevation point errors are all maintained at around 0.04 mm. This indicates an adequate point accuracy.

01
Triangulation

High accuracy measurement

02
High efficiency

Automated measurement

03
Low radiation

Unmanned tunnel

This further enhances automation in measurements, reduces costs, and enhances overall measurement efficiency. The outcomes of this research provide valuable technical means and methods for optimizing the efficiency of alignment and installation measurement in the construction process of large scientific facilities such as CEPC.
However, the environment has great influence on the accuracy of target recognition and angle observation, like there is multiple reflective equipment. In addition, it also needs to design a multi-station setting, if the angle intersection form is not suitable, it will reduce the point accuracy. Finding suitable intersection angles form is not an easy task.

Outlooks

- The size of the target
- Automated target recognition
- Station setting design
- Automated measurement in tunnel
- Unmanned automatic large-scale measurement

Thank you for your attention